

# DOUBLE-BOUNCE SWITCHING\*

George B. Frazier and Steven R. Ashby

Physics International Company  
2700 Merced Street  
San Leandro, California 94577

## Abstract

Double-bounce switching is a technique for exploiting traveling waves in a transmission-line-type pulse forming system to reduce voltage requirements on pulse forming line (PFL) output switches. If a simple PFL (a dc charged ideal transmission line with characteristic impedance  $Z$ ) is switched into a matched load, then peak output power is  $V^2/4Z$ , where  $V$  is output switch voltage. If the PFL is pulse-charged by another transmission line, and if geometries, circuit parameters, and switch points are chosen properly, then the PFL can inject a power much larger than  $V^2/4Z$  into a matched load. This is the principle of double-bounce switching (so called because it exploits a doubly reflected charging wave in the PFL). Data from EAGLE experiments are presented which demonstrate that the technique works in a real geometry.

## Introduction

The use of double-bounce switching in high-power accelerators became possible with the advent of large machines with multiple, transmission-line-type, pulse-compression stages ("a stage" is one transmission line switched into either another transmission line, or a load). In fact, the effect will occur naturally in machines of this type. Such machines have been in existence for many years. They typically use an oil-insulated Marx generator to drive two or more liquid-dielectric, switched transmission lines. The first large example of such a machine built in the United States was GAMBLE II at NRL<sup>1</sup>. A plethora of similar machines followed<sup>2-7</sup>. But the fact that double-bounce switching could be used advantageously in multistage machines was not recognized until 1978.

In June 1978, while working on design concepts for ROULETTE-X<sup>2</sup> (a conceptual design for a very high power radiation simulator), Ian Smith recognized that multiple reflections in multistage pulsed reduce voltage requirements on the final stage. He also recognized that if the technique could be made to work, it would produce an unusual output waveform which, fortuitously, was ideally shaped to drive the pure inductive loads (i.e., imploding plasmas) envisioned for ROULETTE-X. After making preliminary power gain and efficiency estimates, Smith turned the idea over to the staff at Physics International Company for further development. Hugh Calvin, Don Osias, and the authors used digital computer techniques to study the concept in depth, then incorporated it into the design of EAGLE<sup>2</sup>, a large pulsed power test-bed. EAGLE data confirmed that the concept works

in a real generator. Examples of future large generators being designed and built using double-bounce switching are Double-EAGLE<sup>8</sup> and PBFA-II<sup>9</sup>.

The following paragraphs will describe the fundamentals of double-bounce switching and present experimental data from EAGLE which show that the concept works in practice.

## Theory

Consider an ideal transmission line circuit representing the final two pulse-compression stages of a generator, as shown in Figure 1. The first stage, which we will call the "charging pulse-line" (CPL), is of length  $\tau_1$ , impedance  $Z_1$ , and is switched (by closing  $S_1$ ) through inductance  $L_1$  into the second transmission line, the pulse-forming line (PFL) which has length  $\tau_2$ , impedance  $Z_2$ . The PFL then is switched (by closing  $S_2$ ) into a matched-impedance output line through an inductance  $L_2$  at some time  $t$ , after the CPL switch ( $S_1$ ) closes. If  $L_1$  is much greater than  $\tau_2 Z_2$ , the system is a "conventional" pulse-charging circuit. The transmission lines act like lumped elements and produce sinusoidal waveshapes in this case. As  $L_1$  is reduced to approximately  $\tau_2 (Z_1 + Z_2)$  (i.e., when the  $S_1$  risetime is roughly equal to  $\tau_2$ ) transmission line characteristics of the PFL become evident. The initial "charging wave" from the closure of  $S_1$  now can reach peak voltage in a time on the order of the length of the PFL.

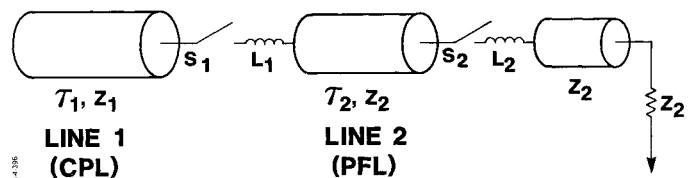


Figure 1. Simplified double-bounce schematic. Line 1 is assumed to be dc charged; in practice, Line 1 usually is pulse-charged conventionally by a transfer capacitor.

This charging wave reflects from the open output switch of the PFL ( $S_2$ ) and begins traveling back toward the CPL. When the wave reaches  $S_1$  (now closed but with inductance  $L_1$ ), some portion is transmitted and some is reflected. The reflected portion travels back toward  $S_2$ . If  $S_2$  now is closed (i.e.,  $T < 3 \tau_2$ ) and has a low enough inductance  $L_2$ , the wave continues out toward the load, as shown schematically in Figure 2.

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This traveling wave does not increase PFL voltage significantly (although PFL voltage can exceed the maximum voltage of  $S_2$ ). This is the essence of double-bounce switching. It allows PFL and  $S_2$  voltages to be reduced without reducing output (load) voltage. This is an enormous advantage in a real machine because the PFL electric field stresses are lowered and the voltage-dependent jitter of  $S_2$  can be reduced.

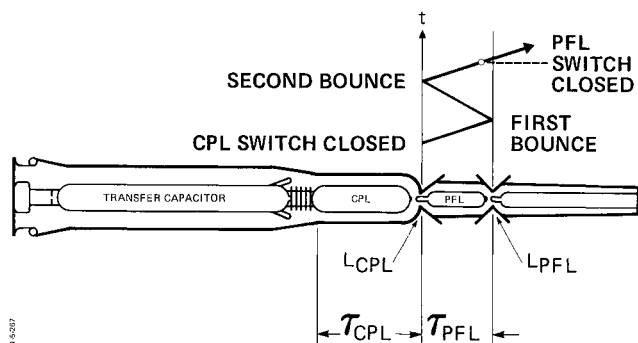


Figure 2. Double-bounce operation in EAGLE. The path of the doubly-reflected PFL "charging wave" is shown schematically by the arrow. The transfer capacitor is charged by a Marx generator.

The value of  $L_1$  (for a given  $Z_1$  and  $Z_2$ ) is crucial. If it is too large, there is no "charging wave". If it is too small, the charging wave passes back into the CPL as opposed to being partially reflected.  $L_2$  must be small to allow the reflected wave to pass through to the output line. Another crucial requirement is that the ends of the PFL show sharp discontinuities so that the waves will be reflected (stray capacitances at either end of the PFL can "filter" the reflection). The ratios  $\tau_1/\tau_2$  and  $Z_1/Z_2$  play a less important but significant role in the performance (their optimum values usually lie between 1.5 and 2.0).

#### EAGLE

EAGLE, shown in the isometric drawing of Figure 3, was designed to allow us to test double-bounce switching. Line lengths were chosen at the points where computer analysis determined double-bounce would work best. The impedances of the tri-plate transmission line sections were designed to be variable about the predicted optimum point by  $\pm 33\%$ . Switch inductances can be adjusted by adding or removing sites. This allowed us to tune the CPL switch (analogous to  $S_1$  in Figure 1) to the optimum value. Adjustable waveguide plates are used in the transition from transmission line to switch geometry to minimize the discontinuity until the inductance of the switch itself is reached.

#### EAGLE Performance

EAGLE performance has demonstrated the usefulness of double-bounce switching. When operated in a conventional switching mode, machine output is limited by water breakdown in the PFL and by PFL switch (analogous to  $S_2$  in Figure 1) inductance. In the double-bounce mode, the breakdown

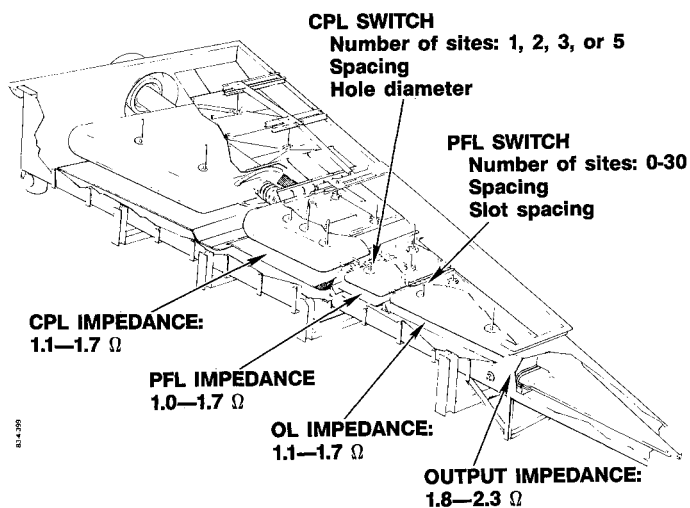


Figure 3. The EAGLE module. Adjustments provided to investigate double-bounce switching are noted.

limitation is at a higher level and occurs in the conventionally charged CPL. We can vary PFL switch timing by changing the water switch gap. As the gap is opened, switchout occurs later (goes toward conventional switching), and the PFL operates closer to the breakdown limit because voltage is increased. The line still is operating in the double-bounce mode when breakdown fractions on the CPL and PFL are equal, and this is the most efficient way to operate the generator in terms of energy transfer from Marx to load.

Waveforms from EAGLE, when operated in the double-bounce mode, are shown in Figure 4. The conventionally-charged CPL voltage is switched out at about 300 ns (4a). The voltage and current at the CPL end of the PFL (4b and 4c) show the initial wave traveling by, then 60 ns later (at time 1 in Figure 4) the wave reflected from the output switch can be seen to cut off current and increase voltage. After another 50 ns (at time 2 in Figure 4), a spike appears on the current waveform that indicates that the output switch has closed and the line electrostatic energy is being discharged. We found this current monitor to be very useful in diagnosing the operation of double-bounce switching.

Examining the voltage waveforms at both the output line end of the PFL and the PFL end of the output line (4d and 4e), we see that the voltage on the PFL continues to rise after switch-out. The output waveshape shows a fast rise (in 5-8 ns) to about 40 percent of the eventual peak voltage, followed by a ramp-like rise (over about 85-90 ns) to peak. This "fast-rise-followed-by-a-ramp" waveshape is peculiar to the double-bounce switching mode. Such a shape is ideal for driving inductive loads (like imploding plasmas) because it can produce flat-top voltage pulses across vacuum tube insulators.

Transfer "efficiencies", considering only electrostatic ( $0.5 \text{ CV}^2$ ) energy in the pulse-forming sections, are shown in Figure 5. By considering only electrostatic energy, we can estimate the contribution of traveling waves in the PFL to delivered output energy. The 258% "efficiency" from PFL to load demonstrates that the PFL energy is contained largely in the traveling waves. Efficiency from the CPL to load

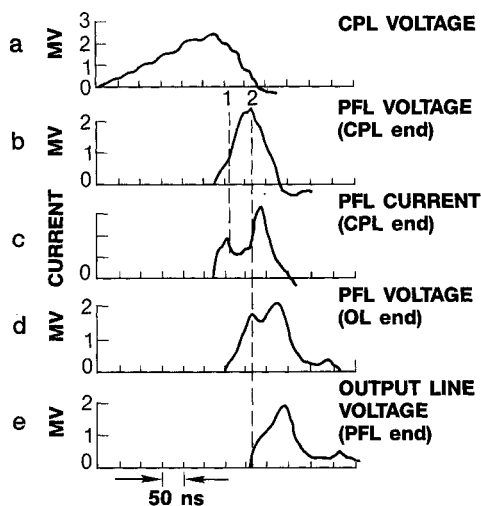


Figure 4. EAGLE double-bounce waveforms. Monitor locations can be inferred from Figure 3. The reflected wave passes the PFL monitor location at time (1). The PFL switch closes at time (2).

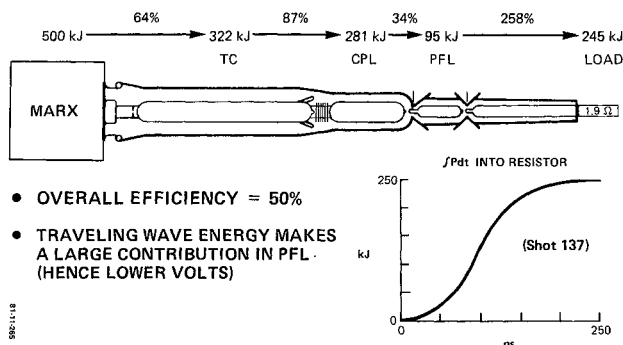


Figure 5. Energy "efficiencies" of EAGLE. For the transmission lines, only electrostatic energy ( $0.5 CV^2$ ) is quoted. Load resistor energy is determined by integrating measured power over time, as shown. The fact that 245 kJ was delivered to the load and only 95 kJ appeared electrostatically in the PFL indicates that over half the load energy came from traveling waves that did not increase PFL voltage.

is 88%, similar to the transfer capacitor (TC) to CPL efficiency, demonstrating that the double-bounce method is equally as efficient as the conventional pulse-charging, but with much reduced stresses in the PFL. The PFL traveling wave energy contributes over half the energy that ultimately is dissipated in the load.

#### Summary

Experiments on EAGLE have demonstrated that double-bounce switching works on a multi-terawatt three-stage pulse generator. The technique reduces stresses in both the final stage and its output switch.

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